

Long GRBs are metallicity-biased tracers of star formation: evidence from host galaxies and redshift distribution

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ABSTRACT

We investigate the mass distribution of long gamma-ray burst (GRB) host galaxies and the redshift distribution of long GRBs by considering that long GRBs occur in low-metallicity environments. We calculate the upper limit on the stellar mass of a galaxy which can produce long GRBs by utilizing the mass-metallicity (M-Z) relation of galaxies. After comparing with the observed GRB host galaxies masses, we find that the observed GRB host galaxy masses can fit the predicted masses well if GRBs occur in low-metallicity $12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$. GRB host galaxies have low metallicity, low mass, and high star formation rate compared with galaxies of seventh data release of the Sloan Digital Sky Survey. We also study the cumulative redshift distribution of the latest *Swift* long GRBs by adding dark GRBs and 10 new GRBs redshifts from TOUGH survey. The observed discrepancy between the GRB rate and the star formation history can be reconciled by considering that GRBs tend to occur in low-metallicity galaxies with $12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$. We conclude that the metallicity cutoff that can produce long GRBs is about $12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$ from the host mass distribution and redshift distribution.

Subject headings: gamma-ray burst: general - stars: formation

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosions in the Universe. Due to their high luminosities, GRBs can be observed throughout most of the observable Universe

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(Lamb & Reichart 2000; Ciardi & Loeb 2000; Cucchiara et al. 2011). So GRBs are ideal tools to study early universe properties, including star formation rate, reionization and metal enrichment history (Wang & Dai 2009; Wang et al. 2012), and so on. According to the duration, GRBs are usually classified into two classes: long GRBs and short GRBs (Kouveliotou et al. 1993). For long GRBs, their host galaxies are typically irregular galaxies with high star formation rate and, especially, a small fraction of long GRBs are associated with Type Ib/c supernovae (SNe) (for a review, see Woosley & Bloom 2006). These GRBs are nearby and sub-luminous. The well-studied SNe that accompany GRBs show evidence for broad lines, indicative of high-velocity ejecta. This type of SNe is a subclassification of Type Ic SNe, called Type Ic-BL. In contrast, short GRBs are usually found at nearby early-type galaxies, with little star formation (for a review, see Nakar 2007). But some short GRB hosts, such as GRBs 100625A and 101219A, are early-type galaxies with moderate star formation (Berger 2009; Fong et al. 2013). So studies on the host galaxies properties are crucial to understand the progenitors and central engines of GRBs.

Some theoretical studies of long GRB progenitors using stellar evolution models suggest that low metallicity may be a necessary condition for a long GRB to occur. For popular collapse models of long GRBs, stars with masses $> 30M_{\odot}$ can be able to create a black hole (BH) remnant (Woosley et al. 1993; Hirschi, Meynet & Maeder 2005). The preservation of high angular momentum and high-stellar mass at the time of collapse (Woosley 1993; MacFadyen & Woosley 1999) is crucial for producing the relativistic jet and high luminosity. Low-metallicity ($0.1 - 0.3Z_{\odot}$) progenitors can theoretically retain more of their mass due to smaller line-driven stellar winds (Kudritzki & Puls 2000; Vink & de Koter 2005), and hence preserve their angular momentum (Yoon & Langer 2005; Yoon, Langer & Norman 2006; Woosley & Heger 2006). Because the wind-driven mass loss of massive stars is proportional to the metallicity.

Observations of long GRB host galaxies also show that they are typically in low metallicity environment, for several local long GRB host galaxies (Sollerman et al. 2005; Stanek et al. 2006) as well as in distant long GRB hosts (Fynbo et al. 2003; Christensen et al. 2004; Gorosabel et al. 2005; Fruchter et al. 2006; Prochaska et al. 2007). Stanek et al. (2006) found that the host galaxy metallicities of five $z < 0.25$ long GRBs were lower than equally luminous dwarf irregular galaxies and concluded that the upper metallicity limit for producing GRBs is about $0.15 Z_{\odot}$. Modjaz et al. (2008) found that long GRB host galaxies had lower metallicities than the host galaxies of nearby broad-lined Type Ic supernovae. Savaglio et al. (2009) examined 46 long GRB host galaxies with 17 metallicity measurements, and found that the hosts had subsolar metallicity with an average metallicity of $1/6$ solar value for 17 of the hosts.

Using a small sample of 5 host galaxies, Han et al (2010) found that the metallicities of the host galaxies tended to fall below the low redshift mass-metallicity (M-Z) relation defined by Sloan Digital Sky Survey (SDSS) catalog. Likewise, Levesque et al. (2010a) compared a much broader sample of long GRB host galaxies and found a similar offset, with long GRB host galaxies exhibiting lower metallicities compared to SDSS galaxies of similar masses. But a few GRB hosts with high metallicity are observed, so that the role of metallicity in driving the GRB phenomena remains unclear and it is still debated (Price et al. 2007; Wolf & Podsiadlowski 2007; Kocevski, West & Modjaz 2009; Graham et al. 2009; Svensson et al. 2010). For excellent reviews, see Fynbo et al. (2013) and Levesque (2013). Mannucci et al. (2011) proposed that the apparent long GRB preference for low-metallicity hosts is due to the fundamental metallicity relation (Kocevski & West 2011). Long GRB hosts have low metallicity because they are effectively selected based on the intense star-formation. By comparing the metallicity of the GRB hosts, Type Ic (Ic-bl) supernovae (SNe), and Type II SNe to each other and to the metallicity distribution of star-forming galaxies, Graham & Fruchter (2013) found that low metallicity must be a fundamental property of long GRB hosts, rather due to the fundamental metallicity relation. Trenti et al. (2013) found that the empirical relation between GRB rate and SFR is due to the GRB preference for low-metallicity.

In this paper, we investigate whether long GRBs occur in low-metallicity environments from observations. We first use empirical models based on the measurements of the redshift evolution of the M-Z relation to estimate the upper limit of the stellar mass of a galaxy that can efficiently produce a GRB, and test the suggestion that GRBs preferentially form in low-metallicity environments with observations. We also compare the GRB host properties with SDSS observations. Then we present the latest *Swift* GRB cumulative redshift distribution considering GRBs occur in low-metallicity environment. The structure of this paper is as follows: in section 2, we give the theoretical mass distribution of GRB host galaxy and compare this with observations. In section 3, we fit the cumulative redshift distribution of *Swift* long GRBs by considering that GRBs occur in low-metallicity environments. Conclusions and discussions are shown in section 4.

2. The mass distribution of GRB host galaxy

In this section, we first estimate the upper limit of the galaxy mass that is capable of producing a GRB using the M-Z relation. Then we compare this result with the host galaxy masses from observations. Last, we will compare the host galaxy properties with galaxies observed by SDSS.

2.1. Theoretical model

Using $\sim 53,000$ galaxies from the SDSS, Tremonti et al. (2004) found a tight correlation between stellar mass and metallicity, so called mass-metallicity (M-Z) relation, which was discovered by Lequeux et al. (1979) for the first time. Savaglio et al. (2005) investigated the empirical redshift-dependent M-Z relation using galaxies at $0.4 < z < 2.0$ from the Gemini Deep Deep Survey (GDDS) and Canada-France Redshift Survey (CFRS). The redshift-dependent M-Z relation can be parameterized as (Savaglio et al. 2005)

$$\begin{aligned} 12 + \log(\text{O/H})_{\text{KK04}} = & -7.59 + 2.53 \log M_{\star} - 0.097 \log^2 M_{\star} \\ & + 5.17 \log t_{\text{H}} - 0.39 \log^2 t_{\text{H}} \\ & - 0.43 \log t_{\text{H}} \log M_{\star}, \end{aligned} \quad (1)$$

where KK04 represents the metallicity scale of Kobulnicky & Kewley (2004), t_{H} is the Hubble time at redshift z in Gyr and M_{\star} is the galactic stellar mass in unit of solar mass. The Hubble time at redshift z is given by

$$t_{\text{H}}(z) = \frac{1}{H_0} \int_z^{\infty} \frac{dz'}{(1+z') \sqrt{\Omega_m(1+z')^3 + \Omega_{\Lambda}}}. \quad (2)$$

In the whole paper, we use $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from the *Wilkinson Microwave Anisotropy Probe* (WMAP) seven-year data (Komatsu et al. 2011). Figure 1 shows the metallicity as a function of stellar mass at different redshifts. Studies at the redshift range $z \sim 1 - 3$ (Mannucci et al. 2009; Zahid et al. 2011; Finkelstein et al. 2011), and high redshift $z \sim 3 - 5$ (Laskar et al. 2011), show that the M-Z relation may keep the same overall trend.

In order to model the effects of a metallicity cutoff on the mass distribution of GRB host galaxies, the number density of galaxies and the number of stars being produced in those galaxies as a function of galactic stellar mass are also needed. Drory & Alvarez (2008) found the star-formation rate as a function of stellar mass and redshift spanning $9 < \log M_{\star} < 12$ and $0 < z < 5$ using data from FORS Deep Field survey. They parameterize the observed star formation rate-stellar mass relation as

$$\text{SFRM}(M_{\star}, z) = \text{SFRM}_0 \left(\frac{M_{\star}}{M_0} \right)^{\beta} \exp \left(-\frac{M_{\star}}{M_0} \right), \quad (3)$$

where $\beta = 0.6$, SFRM_0 is the overall normalization and M_0 represents the break mass the mass above which the average star formation rate begins to decline. The best fit parameterizations from Drory & Alvarez (2008) are

$$\text{SFRM}_0(z) \approx 3.01(1+z)^{3.03} M_{\odot} \text{ yr}^{-1}, \quad (4)$$

$$M_0(z) \approx 2.7 \times 10^{10} (1+z)^{2.1} M_{\odot}. \quad (5)$$

We show star-formation rate as a function of stellar mass from $z = 0$ to $z = 5$ in Figure 2.

The galactic stellar mass function is commonly described by a Schechter function. We use the Schechter form derived by Fontana et al. (2006) measured from the GOODS-MUSIC field,

$$\phi(M, z) = \phi^*(z) \ln(10) [10^{M-M^*(z)}]^{1+\alpha^*(z)} \exp(-10^{M-M^*(z)}), \quad (6)$$

where $M = \log_{10}(M_*/M_\odot)$, M_* is the stellar mass of the galaxy and the parametric functions obey:

$$\begin{aligned} \phi^*(z) &= \phi_0^* (1+z)^{\phi_1^*} \\ \alpha^*(z) &= \alpha_0^* + \alpha_1^* z \\ M^*(z) &= M_0^* + M_1^* z + M_2^* z^2 \end{aligned}$$

The parameter values are given as: $\phi_0^* = 0.0035$, $\phi_1^* = -2.20$, $\alpha_0^* = -1.18$, $\alpha_1^* = -0.0082$, $M_0^* = 11.16$, $M_1^* = 0.17$ and $M_2^* = -0.07$.

In order to know the total number of stars being produced as a function of stellar mass, we compute the galaxy-weighted star formation rate by multiplying equation (3) by equation (6). The total star formation rate is shown in Figure 3. The weighted star formation rate peaks at intermediate masses between $10^{10} M_\odot$ and $10^{11} M_\odot$.

2.2. Comparison to GRB host galaxy observations

The GRB host galaxy can be observed when the bright emission of the GRB is gone. Often the ionized gas (the H II regions) is emitting with sufficient intensity so emission lines can be detected (Savaglio 2006). Savaglio et al. (2009) compiled a sample of 40 long GRB host galaxies through a combination of optical and NIR observations. They found that GRB host galaxies exhibit a wide range of stellar mass and star formation rates, although as a whole they tend toward low stellar mass, relatively dim, high specific star-forming systems. They also estimated that the average stellar mass is $10^{9.3} M_\odot$. Besides the data of these 40 host galaxies, we also use the latest GRB host data from GRB Host Studies (GHostS), which is accessible at the Web site www.grbhosts.org. The total number of GRB host galaxies with estimated mass is 58 (hereafter SG sample), which are listed in Table 1. The metallicities are converted to KK04 scale based on Table 3 of Kewley & Ellison (2008). In Figure 4, we show the host galaxy mass distribution of SG sample with black dots. The solid line represents the upper limits of the stellar mass of a GRB host galaxy given a metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$. The dashed lines represent the scatter in the upper limit imposed by the 1σ scatter of the M-Z relation. The most long GRB host galaxy masses are well below upper limits of the stellar mass of a GRB host galaxy given a metallicity

cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$ excluding a few GRBs. Levesque et al. (2010a, hereafter L10) presented a sample of 16 long GRB host galaxies, including 13 GRBs with host galaxy mass determination. They also concluded that long GRBs tend to occur in host galaxies with lower metallicities than the general population. We show the host mass distribution in Figure 4 with open dots. The long GRB host galaxy masses of L10 are below the upper limits due to metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$ except for a few GRBs. There are some uncertainties when measuring the metallicities of GRBs’ explosion regions at high-redshifts, such as chemical inhomogeneity (Levesque et al. 2010b; Niino 2011). Long GRB locates in a lower metallicity region of its host, but the galactic average measured. We will discuss the probability as follows. For GRB 020819, the host metallicity is $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 9.0 \pm 0.1$ (Levesque et al. 2010b), which is the highest metallicity determined for a long GRB to date. Interestingly, some theoretical models predict that long GRBs can occur in high metallicity environment (Podsiadlowski et al. 2010; Georgy et al. 2012). For GRB 080319C, the apparent brightness of the host galaxy may be overestimated. This burst is a dark burst with large extinction ($A_V = 0.65$ mag) (Perley et al. 2009). There is an intervening Mg II system at $z = 0.81$ along the line of sight of GRB 080319C (Fynbo et al. 2009). The apparent brightness of the host galaxy may be overestimated due to the contamination of Mg II system. So the mass of host galaxy should be overestimated.

In Figure 5, we show the observed metallicities of GRB host galaxies taking from Savaglio et al. (2009) and Levesque et al. (2010a). The solid lines represent the predictions from the empirical model of equation (1), for different stellar masses. We can see that the long GRBs are below the theoretical prediction of equation (1) except for GRB 020819. As discussed above, more precise localization of this burst is needed to draw robust conclusions. The recent observations of the afterglow of GRB 090323 at redshift $z = 3.57$ by Savaglio et al. (2012) shows evidence for two damped Ly α (DLA) systems with supersolar metallicities. But high-resolution observation is needed to check whether one of them is the host galaxy.

If long GRBs are unbiased tracers of star formation throughout the universe, their observed host mass distribution should have a largest probability at the peak in the galaxy-weighted star formation rate. We will test this expectation below. The long GRB host galaxy median mass of SG sample is $10^{9.45} M_\odot$, which is obviously contradict the prediction from Figure 3. We should compare the observed host mass distribution to the expected mass distribution of all star-forming galaxies at a given redshift, because the detection effects should not affect this region of the observed distribution. This problem is also discussed in Kocevski et al. (2009). In order to use much more observation data, we carry out this test around $z = 1$. In Figure 7, we show the GRB host mass distribution of SG sample between $0.75 \leq z \leq 1.25$ as histogram. The number of long GRBs with host mass determination in this redshift range is 16. The galaxy-weighted star formation rate as a function of galactic

stellar mass at $z = 1$ is shown as the solid line in Figure 7. After considering the mass limits due to sharp metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$, we calculated the galaxy-weighted star formation rate as a function of galactic stellar mass, which is shown as the dashed line in Figure 7. The average host galaxy mass of this sub-SG sample is $10^{9.50} M_{\odot}$. After considering the metallicity cutoff, the peak of the galaxy-weighted star formation rate will shift from $10^{10.3} M_{\odot}$ to $10^{9.7} M_{\odot}$, which is much more consistent with the observation.

2.3. GRB host galaxy observations compared to SDSS galaxy

We use the galaxies that are well measured by SDSS-DR7 project (Abazajian et al. 2009). The derived galaxy properties from the MPA-JHU are available at <http://www.mpa-garching.mpg.de> which contains 927 552 galaxies. The detailed analysis process can be found in Kauffmann et al. (2003) and Salim et al. (2007) for stellar masses, Brinchmann et al. (2004) for SFRs and Tremonti et al. (2004) for metallicities. We use the information of galaxies, including dust extinction A_V , stellar masses, star formation rates, and metallicities. Although the redshifts of galaxies from SDSS are less than 0.6, the redshifts of our GRB host galaxy sample are also mainly less than 1.0. The median redshift of SDSS is 0.15, and the median redshift of GRB host is 1.13. In Figure 8, we compare the metallicities of GRB host galaxy and SDSS galaxy with same masses. The gray points represent individual galaxies of SDSS. The open dots are binned metallicities of SDSS galaxies in mass range, and filled dots are the metallicities of GRB host galaxy from observation. The metallicities of GRB host galaxy are well below those of SDSS galaxies. So GRBs prefer to occur in low-metallicity galaxies. Figure 9 illustrates the GRB host galaxy masses compared to masses of SDSS galaxies at the same redshift. The gray points represent individual galaxies of SDSS. The filled dots are the masses of GRB host galaxies from observations, while the open dots are binned masses of SDSS galaxies. By comparing the averaged masses of SDSS galaxies with the those of GRB hosts galaxies, we find that long GRBs prefer to occur in low mass galaxies. Figure 10 presents the metallicities and SFRs of GRB host galaxies compared to SDSS galaxies. The gray points represent individual galaxies of SDSS. The filled dots are the value of GRB host galaxy from observation, while the open dots are binned SFRs of SDSS galaxies. Obviously, long GRBs prefer to occur in star-forming galaxies. We also show SFRs and galaxy masses in Figures 11. The gray points represent individual galaxies of SDSS. Filled dots are the value of GRB host galaxy from observation and open dots are binned SDSS value. By comparing the averaged SFRs of SDSS galaxies with the those of GRB hosts galaxies, we find that long GRBs prefer to occur in galaxies with high SFRs. Figure 12 shows dust extinction A_V . We can see that there is no difference between dust extinction A_V from GRB host galaxies and averaged SDSS value. From these figures, we can conclude that long GRB host galaxies

have low masses, low metallicities, and high SFRs comparing with the galaxies of SDSS. This conclusion is consistent with observations, such as Fynbo et al. (2003), Christensen et al. (2004), Gorosabel et al. (2005), Fruchter et al. (2006) and Prochaska et al. (2007).

3. Cumulative redshift distribution of *Swift* long GRBs

In order to study the cumulative redshift distribution of *Swift* long GRBs (i.e. the observed duration time is larger than 2 seconds), we first use long GRBs till GRB 111107A observed by *Swift*, including dark GRBs from Perley et al. (2009, 2013), Greiner et al. (2011), and Krühler et al. (2011). This subsample is also used in Wang (2013). We take the redshift, isotropic energy E_{iso} and durations of GRBs from Butler et al. (2007, 2010), and Sakamoto et al. (2011). The luminosity is computed from $L_{\text{iso}} = E_{\text{iso}}/[T_{90}/(1+z)]$. The Perley et al. (2009) work provides us with six redshifts of dark GRBs in our sample. Greiner et al. (2011) and Krühler et al. (2011) have provided three additional redshifts of dark GRBs in our sample. Jakobsson et al. (2012) and Hjorth et al. (2012) obtained 10 new GRB redshifts based on host galaxy spectroscopy at the ESO Very Large Telescope, including GRB 050406, GRB 050502B, GRB 050819, GRB 050822, GRB 051001, GRB 051117B, GRB 060719, GRB 070103, GRB 070129, GRB 070419B, which are also including in our sample. We also include 3 three GRBs from Perley et al. (2013). So there are 192 GRBs in our catalog. We list dark GRBs in Table 2.

The fraction of star formation occurring in galaxies with metallicities lower than Z_{crit} , which can be expressed as (Stanek et al. 2006)

$$\Psi(z) = \frac{\int_0^{M_{\text{crit}}(z)} \text{SFRM}(M, z) \phi(M, z) dM}{\int_0^\infty \text{SFRM}(M, z) \phi(M, z) dM} \quad (7)$$

where $\text{SFRM}(M, z)$ is the star formation rate - stellar mass relation defined in equation (4) and $\phi(M, z)$ is the galaxy stellar mass function defined in equation (6).

The expected redshift distribution of GRBs is

$$\frac{dN}{dz} = F_0 \frac{\Psi(z) \dot{\rho}_*(z)}{\langle f_{\text{beam}} \rangle} \frac{dV/dz}{1+z}, \quad (8)$$

where F_0 represents the ability both to detect the trigger of burst and to obtain the redshift, GRBs that are unobservable due to beaming are accounted for through f_{beam} and $\dot{\rho}_*(z)$ is the star formation rate. For the star formation rate, we use the result of Hopkins & Beacom (2006), which reads

$$\dot{\rho}_*(z) \propto \begin{cases} (1+z)^{3.44}, & z \leq 0.97, \\ (1+z)^{-0.26}, & 0.97 < z < 4.0. \end{cases} \quad (9)$$

In a flat universe, the comoving volume is calculated by

$$\frac{dV}{dz} = 4\pi D_{\text{com}}^2 \frac{dD_{\text{com}}}{dz}, \quad (10)$$

where the comoving distance is

$$D_{\text{com}}(z) \equiv \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \quad (11)$$

In the calculations, we use $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from the *Wilkinson Microwave Anisotropy Probe* (WMAP) seven-year data (Komatsu et al. 2011). So the number of observed GRBs in the redshift range $z_1 < z < z_2$ is

$$N(z_1, z_2) = \frac{F_0}{f_{\text{beam}}} \int_{z_1}^{z_2} dz \Psi(z) \dot{\rho}_*(z) \frac{dV/dz}{1+z}, \quad (12)$$

where F_0 represents the ability both to detect the trigger of burst and to obtain the redshift. The cumulative distribution of GRB redshift can be expressed as

$$\frac{N(< z)}{N(< z_{\text{max}})} = \frac{N(0, z)}{N(0, z_{\text{max}})}. \quad (13)$$

Because the observed star formation rate is now reasonably well measured from $z = 0 - 4$, so we consider GRBs in this redshift range. In order to avoid the selection effects, we choose the luminosity cut $L_{\text{iso}} > 10^{51} \text{ erg s}^{-1}$ (Yüksel et al. 2008) in the redshift range $0 - 4$. We have 111 GRBs in this sub-sample. The cumulative redshift distribution of these 92 GRBs is shown in Figure 13. The dashed line shows the GRB rate inferred from the star formation history of Hopkins & Beacom (2006). The black line shows the GRB rate inferred from equations (7) and (8) using $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$. The cyan, blue and red lines show the GRB rate inferred from equations (7) and (8) using $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.8$, $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.6$ and $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.5$, respectively. The metallicity cutoff about $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$ can well produce the cumulative redshift distribution of *Swift* long GRBs. We find that the maximum probability occurs at a metallicity cutoff about $Z_{\text{crit}} = 12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$ using the Kolmogorov-Smirnov test. Li (2008) also found that the cumulative redshift distribution of 32 long GRBs can be well fitted by considering metallicity cutoff $Z \sim 0.3Z_\odot$. Hao & Yuan (2013) found that a metallicity cut of $Z \sim 0.6Z_\odot$, which is roughly consistent with our result. The presence of a host galaxy metallicity ceiling $12 + \log(\text{O}/\text{H}) \leq 8.85$ above which GRBs are suppressed is highly consistent with the available data is found using the second Swift BAT catalog of GRBs (Robertson & Ellis 2012).

4. Conclusions and discussion

In this paper, we have investigated the mass distribution of long gamma-ray burst (GRB) host galaxies and the redshift distribution of long GRBs. We also compare GRB host galaxies to the galaxies of SDSS. We calculate the upper limit on the stellar mass of a galaxy which can produce long GRBs by utilizing the mass-metallicity (M-Z) relation of galaxies. After comparing with the GRB host galaxies masses from observation, we find that the observed GRB host galaxy masses can fit the predicated masses well if GRBs occur in low-metallicity $12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$. GRB host galaxies have low metallicity, low mass, and high star formation rate compared with galaxies of seventh data release of the Sloan Digital Sky Survey. We also study the cumulative redshift distribution of the latest *Swift* long GRBs by adding dark GRBs and 10 new GRBs redshifts from TOUGH survey. We find that the observed discrepancy between the GRB rate history and the star formation history can be reconciled by considering that GRBs tend to occur in low-metallicity galaxies with $12 + \log(\text{O}/\text{H})_{\text{KK04}} < 8.7$.

We conclude that there is marginal evidence to indicate that GRB host galaxies are metallicity biased tracers of star formation. We find that the galaxy mass function that includes a smooth decrease in the efficiency of producing GRBs in galaxies of metallicity above $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$ accommodates a majority of the measured host masses. This is in rough agreement with the metallicity cutoff $12 + \log(\text{O}/\text{H})_{\text{KK04}} \sim 8.66$ at low redshift found by Modjaz et al. (2008).

In theory, there are at least three conditions for producing a GRB with a collapsar (Petrovic et al. 2005; Bromm & Loeb 2006). First, in order to form a black hole, the progenitor star must be very massive. Second, the hydrogen envelope must be lost in order for a relativistic jet to penetrate through the star. Third, the central core of progenitor star must have sufficient angular momentum. But a single massive star has difficulty to fulfill these three requirements, because of magnetic core-envelope coupling and strong wind. In order to overcome the two problems, rapidly rotating stars with low metallicity about $0.1 - 0.3Z_{\odot}$ have been investigated (Yoon & Langer 2005; Woosley & Heger 2006). But some GRB host galaxies may have much higher metallicity, such as GRB 020819. So the theory of long GRB formation should be possible to produce GRBs at high metallicity. Georgy et al. (2012) studied how rotation modifies the evolution of a given initial mass star towards the Wolf-Rayet phase and how it impacts the rate of long GRBs. For solid-body rotation, the explosion of long GRB is restricted to low metallicity. For internal differential rotation, metallicity also plays an important role, but long GRB could occur at larger metallicity, probably at higher than solar metallicity (Georgy et al. 2012). Non-rotating and rotating star evolutions with metallicity $z = 0.002$ in the mass range from 0.8 to $120 M_{\odot}$ had been

investigated by Georgy et al. (2013). They also found that rotation is very important in the stellar evolution. Groh et al. (2013) investigated the fundamental properties of core-collapse supernova and GRB progenitors from single stars at solar metallicity. They found that the GRB progenitors at solar metallicity have a WO spectral type. Fryer et al. (1999) and Podsiadlowski et al. (2010) showed that a massive binary can eject the common envelope, and then produce long GRB at high metallicity. More recently, numerical simulations of Population (Pop) III star formation show that they may form in binary or small multiple systems (Stacy et al. 2010). Pop III stars in binary or small multiple systems may produce long GRBs efficiently (Bromm & Loeb 2006).

Acknowledgements

We thank the referee for detailed and very constructive suggestions that have allowed us to improve our manuscript. This work is supported by the National Basic Research Program of China (973 Program, grant 2014CB845800) and the National Natural Science Foundation of China (grants 11373022, 11103007, and 11033002).

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Table 1. GRB host properties

GRB	z	$\log(M) [M_{\odot}]$	$\text{SFR} [M_{\odot}/\text{yr}]$	$12+\log(\text{O}/\text{H})$	A_V	Ref
970228	0.695	8.65 ± 0.05	0.53	8.47	0.63	1,2,3
970508	0.835	8.52 ± 0.10	1.14	...	0.84	3,4,5
970828	0.960	9.19 ± 0.36	0.87	...	2.13	5,6,7
971214	3.420	9.59 ± 0.40	11.40	...	1.35	2,5,8
980425	0.0085	9.21 ± 0.52	0.21	8.16	1.73	5,9,10,11
980613	1.097	8.49 ± 0.21	4.70	...	1.02	2,12
980703	0.966	9.33 ± 0.36	16.57	8.14	1.10	3,5,13
990123	1.600	9.42 ± 0.49	5.72	...	1.21	3,5
990506	1.310	9.48 ± 0.18	2.50	...	...	5,14
990705	0.842	10.20 ± 0.76	6.96	...	...	5,9,15,16
990712	0.434	9.29 ± 0.02	2.39	8.10	0.39 ± 0.09	3,17
991208	0.706	8.53 ± 0.37	4.52	8.02	0.49	3,18
000210	0.846	9.31 ± 0.08	2.28	...	0.05	3,19
000418	1.118	9.26 ± 0.14	10.35	...	1.30	3,14
000911	1.058	9.32 ± 0.26	1.57	...	0.80	20,21
000926	2.036	9.52 ± 0.84	2.28	...	0.58	3
010222	1.480	8.82 ± 0.26	0.34	...	...	5,22,23,24,25
010921	0.451	9.69 ± 0.13	2.50	8.15	1.06 ± 0.62	3,25,26
011121	0.362	9.81 ± 0.17	2.24	8.60	0.38	27,28
011211	2.141	9.77 ± 0.47	4.90	...	...	29
020405	0.691	9.75 ± 0.25	3.74	8.44	$1.9^{+0.6}_{-0.6}$	25,30
020813	1.255	8.66 ± 1.41	6.76	...	...	7,25,31
020819	0.411	10.50 ± 0.14	6.86	8.98	1.8 ± 0.5	32
020903	0.251	8.87 ± 0.07	2.65	8.22	0.8 ± 0.2	25,33,34
021004	2.327	10.20 ± 0.18	3.12	...	...	35,36,37
021211	1.006	10.32 ± 0.63	3.01	...	1.78	25
030328	1.520	8.83 ± 0.52	3.20	...	1.06	38
030329	0.168	7.74 ± 0.06	0.11	7.97	0.58	39,40
030528	0.782	8.82 ± 0.39	15.07	8.10	...	41,42
031203	0.1055	8.82 ± 0.43	12.68	8.02	0.34 ± 0.05	43,44
040924	0.858	9.20 ± 0.37	1.88	8.23	...	25,45
041006	0.712	8.66 ± 0.87	0.34	...	...	25,46
050223	0.584	9.73 ± 0.36	1.44	8.66	...	47
050826	0.296	9.79 ± 0.11	9.13	...	...	48,49
051022	0.8070	10.42 ± 0.18	36.46	8.65	...	50,51
060218	0.0334	7.78 ± 0.08	0.05	8.13	0.49 ± 0.24	52,53,54,55
060505	0.0889	9.41 ± 0.01	0.43	8.44	0.63 ± 0.01	56
060614	0.125	7.95 ± 0.13	0.01	8.24	...	57,58,59,60
061126	1.159	10.31 ± 0.47	2.38	...	...	61
061222	2.088	8.04 ± 0.21	...	...	...	62,63
070306	1.496	10.36 ± 0.21	...	...	0.13	63,64,65
070714B	0.9224	9.45 ± 0.24	0.90 ± 0.10	...	...	66,67,68
070802	2.455	9.85 ± 0.16	...	...	0.74	63,69,70
080207	2.086	11.51 ± 0.11	...	...	2.36	63,71,72
080319C	1.950	12.22 ± 0.47	...	...	...	62,63,69
080605	1.64	9.60 ± 0.30	...	...	...	69,73

Table 1—Continued

GRB	z	$\log(M) [M_{\odot}]$	SFR [M_{\odot}/yr]	$12+\log(\text{O}/\text{H})$	A_V	Ref
080607	3.036	9.90 ± 0.50	...	...	1.15	63,74
080805	1.504	9.70 ± 0.20	...	...	...	65
081109	0.979	9.82 ± 0.09	9.90	...	1.25	63,65
090205	4.650	10.83 ± 0.53	...	...	...	75
090323	3.577	11.20 ± 0.75	...	...	...	76,77
090328	0.735	9.82 ± 0.08	3.60 ± 0.20	...	...	76,78
090417B	0.345	9.53 ± 0.43	...	...	...	63,79
090926B	1.240	10.10 ± 0.40	...	...	...	65
091127	0.490	8.70 ± 0.20	0.22 ± 0.01	8.60	...	80,81
100418	0.624	9.28 ± 0.28	1.90 ± 0.10	...	...	82,83
100621	0.542	8.98 ± 0.14	...	...	...	65,84
120624B	2.20	10.60 ± 0.20	23.0	...	1.0	85
130427	0.34	9.00 ± 0.15	0.90	8.70	0.05	86,87
130702	0.145	7.90 ± 0.20	0.05	8.50	...	88,89

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Table 2. GRB Catalog

GRB	z	$E_{\text{iso}} [10^{52} \text{ erg}]$	$T_{90} [\text{s}]$	$L_{\text{iso}} [10^{52} \text{ erg s}^{-1}]$
Dark GRBs				
050915A	2.53	$1.94^{+2.6}_{-0.6}$	53.4	$0.13^{+0.18}_{-0.04}$
060210	3.91	$42.0^{+35.0}_{-8.0}$	242	$0.85^{+0.71}_{-0.16}$
060510B	4.94	$23.0^{+10.0}_{-4.0}$	263	$0.52^{+0.23}_{-0.09}$
061222A	2.09	$67.4^{+35.3}_{-12.8}$	96.0	$2.17^{+1.14}_{-0.41}$
070521	1.35	$25.2^{+22.0}_{-8.8}$	38.6	$1.54^{+1.34}_{-0.53}$
081109	0.98	$4.1^{+2.6}_{-1.0}$	221	$0.037^{+0.023}_{-0.020}$
080319C	1.95	$6.0^{+5.0}_{-1.0}$	29.5	$0.60^{+0.50}_{-0.10}$
080516	3.60	$12.0^{+6.0}_{-4.8}$	5.75	$9.57^{+4.79}_{-3.83}$
081228	3.40	$3.7^{+1.6}_{-1.3}$	3.00	$5.36^{+2.30}_{-1.84}$
051008	2.90	$9.6^{+1.5}_{-1.0}$	16.0	$2.34^{+2.10}_{-1.25}$
090404	3.00	$5.9^{+1.8}_{-2.3}$	84.0	$0.29^{+2.42}_{-2.54}$
090709A	1.80	$20.9^{+3.6}_{-2.5}$	89.0	$0.66^{+3.35}_{-2.83}$
TOUGH GRBs				
050406	2.7	$0.23^{+0.20}_{-0.08}$	5.0	$0.17^{+0.15}_{-0.06}$
050502B	5.2	$3.84^{+7.61}_{-0.93}$	17.4	$1.37^{+2.71}_{-0.33}$
050819	2.5	$1.02^{+1.48}_{-0.34}$	47	$0.076^{+0.11}_{-0.0025}$
050822	1.434	$2.55^{+3.15}_{-0.26}$	105	$0.059^{+0.073}_{-0.006}$
051001	2.43	$2.09^{+0.56}_{-0.29}$	56	$0.128^{+0.034}_{-0.018}$
051117B	0.481	$0.018^{+0.02}_{-0.005}$	10.5	$0.0026^{+0.0029}_{-0.0007}$
060719	1.532	$1.60^{+1.85}_{-0.25}$	57	$0.071^{+0.082}_{-0.011}$
070103	2.62	$0.58^{+0.59}_{-0.14}$	10.9	$0.191^{+0.195}_{-0.046}$
070129	2.338	$2.89^{+1.24}_{-0.55}$	92	$0.105^{+0.045}_{-0.02}$
070419B	1.959	$15.7^{+10.8}_{-2.94}$	134	$0.346^{+0.238}_{-0.065}$

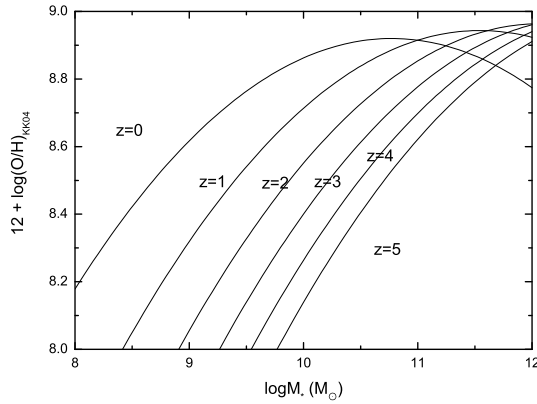


Fig. 1.— Redshift evolution of galaxy mass-metallicity relation derived by Savaglio et al. (2005).

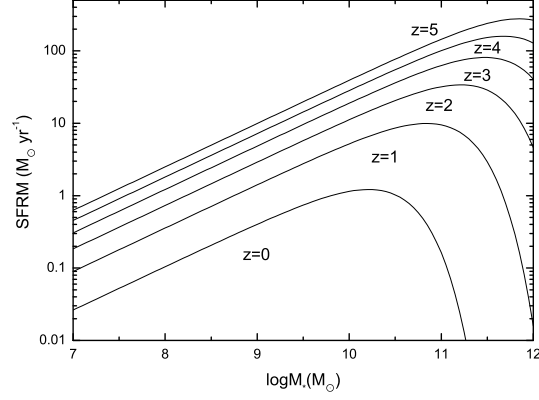


Fig. 2.— Average star formation rate as a function of stellar mass at different redshifts. The peak rates evolve to high stellar mass with increasing redshift.

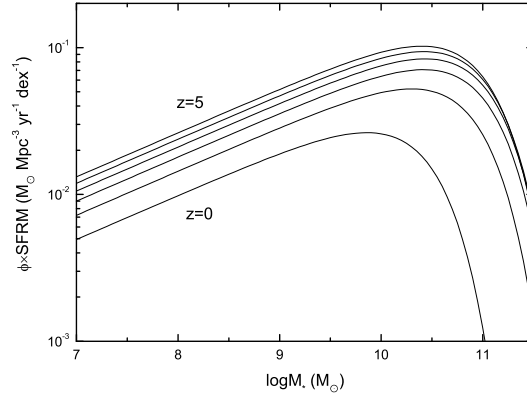


Fig. 3.— Total star formation rate as a function of stellar mass at different redshifts ($z = 0$ to $z = 5$ from bottom to top).

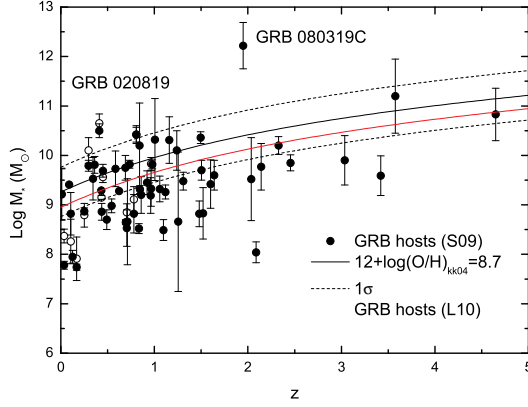


Fig. 4.— GRB host galaxy mass distribution. The host galaxy masses are taken from Savaglio et al. (2009) and GHostS. The solid lines represent the upper limits of the stellar mass of a GRB host galaxy given a metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$ (black), and $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.6$ (red). The dashed lines represent the scatter in the upper limit imposed by the 1σ scatter of the M-Z relation.

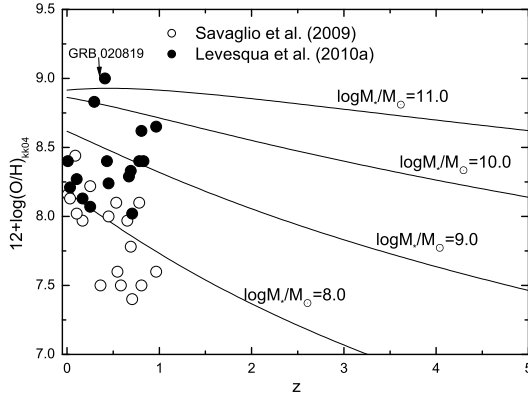


Fig. 5.— Metallicity as a function of redshift. The observed GRB host galaxy metallicities are taken from Savaglio et al. (2009) and Levesque et al. (2010a). The curves are predictions from the empirical model of equation (1), for different stellar masses.

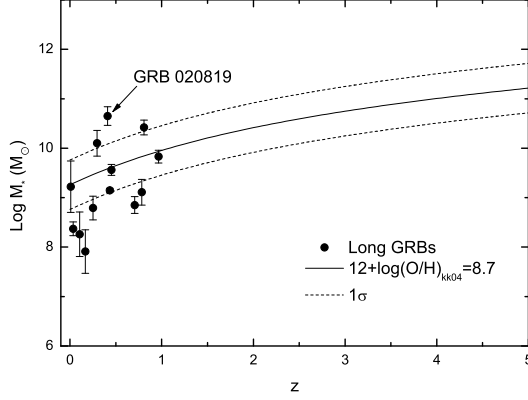


Fig. 6.— GRB host galaxy mass distribution. The host galaxy masses are taken from Levesque et al. (2010a). The solid line represents the upper limits of the stellar mass of a GRB host galaxy given a metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$. The dashed lines represent the scatter in the upper limit imposed by the 1σ scatter of the M-Z relation.

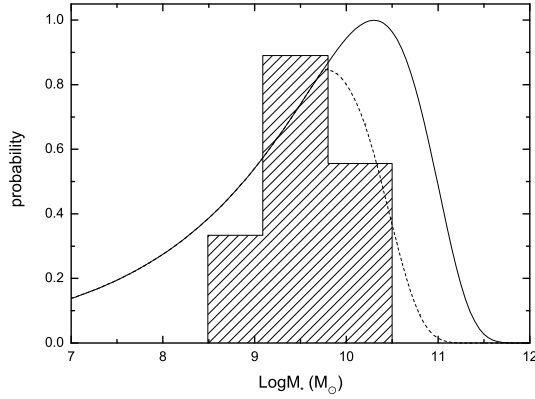


Fig. 7.— GRB host mass distribution as measured by sub-SG sample between $0.75 < z < 1.25$. The solid line is the galaxy-weighted star formation rate as a function of galactic stellar mass at $z = 1$. The mass limit due to sharp metallicity cutoff of $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$ is represented by the dashed line. The peak of the sub-SG sample is much more consistent with the the expected peak of a biased galaxy-weighted star formation rate.

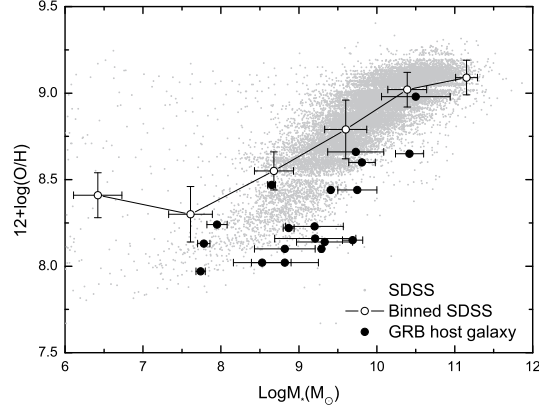


Fig. 8.— Comparison between the metallicities of GRB host galaxies and SDSS galaxies. The gray points represent individual galaxies of SDSS. The open dots are SDSS binned metallicities, and filled dots are the metallicities of GRB host galaxies from observations. The metallicities of GRB hosts are well below the values of SDSS galaxies.

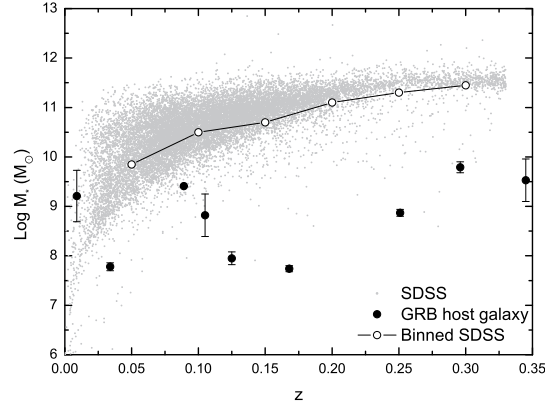


Fig. 9.— Comparison between the masses of GRB host galaxies and SDSS galaxies. The gray points represent individual galaxies of SDSS. The filled dots are the masses of GRB host galaxies from observations, and the open dots are binned SDSS masses.

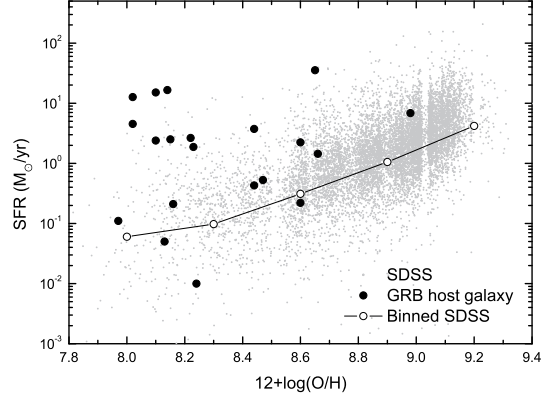


Fig. 10.— Comparison between the metallicities and SFRs of GRB host galaxies and SDSS galaxies. The gray points represent individual galaxies of SDSS. Filled dots are the value of GRB host galaxies from observations, and the open dots are SDSS binned SFRs.

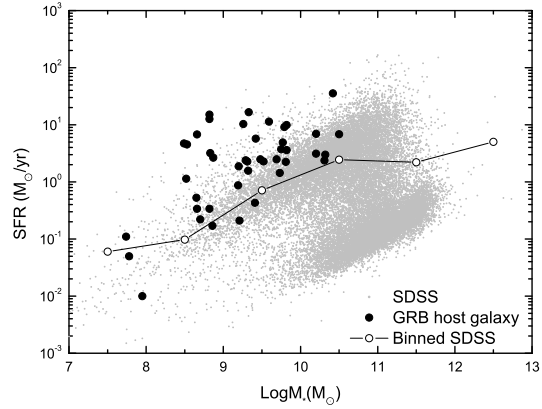


Fig. 11.— Comparison between the SFR of GRB host galaxies and SDSS galaxies. The gray points represent individual galaxies of SDSS. Filled dots are the SFRs of GRB host galaxies from observations and open dots are binned SDSS SFRs.

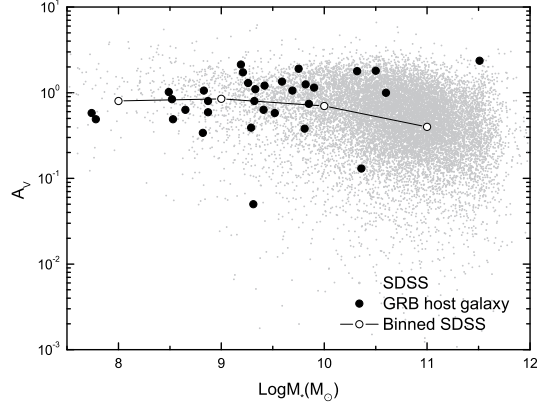


Fig. 12.— Comparison between the dust extinction of GRB host galaxies and SDSS galaxies. The gray points represent galaxies observed by SDSS. Filled dots are the dust extinction of GRB host galaxies from observations and open dots are binned SDSS dust extinction A_V .

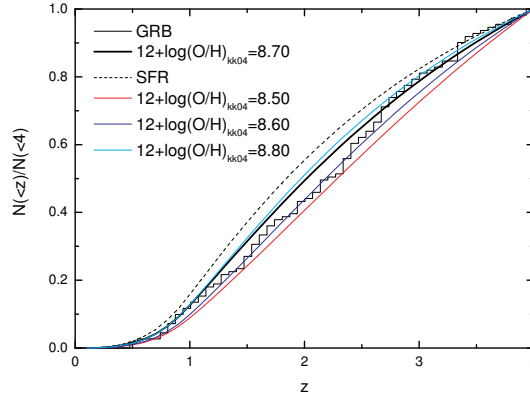


Fig. 13.— Cumulative distribution of 111 *Swift* GRBs with $L_{\text{iso}} > 10^{51} \text{ erg s}^{-1}$ in $z = 0 - 4$ (stepwise solid line). The dashed line shows the GRB rate inferred from the star formation history of Hopkins & Beacom (2006). The solid lines show the GRB rate inferred from equations (7) and (8) using different metallicity cutoffs.